

Spectroscopic Study of SU UMa-type Dwarf Nova YZ Cnc during its 2002 Superoutburst

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Abstract We report time-resolved spectroscopic observations of the SU Ursae Majoris dwarf nova, YZ Cnc, for 2 nights over 11 hrs during its 2002 January superoutburst. The spectra only show absorption-line profiles in the first day. But the lines display blue and red troughs, with “W” profiles in the second day. The radial velocity curve of the absorption troughs and emission peaks of H β has an amplitude of 49 ± 10 km s⁻¹ and a phase offset of -0.07 ± 0.04 , which are very similar to those measured in quiescence; however, the γ velocity deviates strongly from the systemic velocity measured in quiescence, showing variation of the order of ± 60 km s⁻¹. And large shifts of ~ 70 km s⁻¹ and ~ 0.09 , for the orbital-averaged velocity and phase respectively, are also found in our observations. All these phenomena can be well explained with a precession of an eccentric disk and we conclude that these phenomena are the characteristic products of an eccentric accretion disk.

Key words: accretion, accretion disks – binaries: close – novae, cataclysmic variables – stars: dwarf novae – stars: individual (YZ Cancri)

1 INTRODUCTION

YZ Cnc is a member of the class of SU UMa type dwarf novae, in which normal outbursts (i.e., short outbursts) are occasionally interspersed by longer and brighter distinctive superoutbursts, accompanying superhump phenomena. Superhumps are large amplitude luminosity variations with a period usually a few percent longer than the orbital period of the binary system. And this is generally thought to arise from the interaction of the

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donor star orbit with slowly progradely precessing non-axisymmetric accretion disk. The eccentricity of the disk arises because a 3:1 resonance occurs between the donor star orbit and motion of matter in the outer disk (for a good review, see Warner 1995).

YZ Cnc is remarkable in several respects. Photometric study showed that YZ Cnc has a visual magnitude of ~ 14.5 in quiescence and ~ 10.5 in outburst and is one of the most active cataclysmic variables because of the large flickering amplitude of 0.75 mag peak to peak (Moffett & Barnes 1974). It has a very short recurrence time of ~ 11.3 days (Vorob'yeva & Kukarkin 1961). Patterson (1979) discovered superhumps in the light curve with a period of 0.09204 day of YZ Cnc and defined it as an SU UMa type star, and his continuous study (Patterson 1981) with high-speed photometric observations of YZ Cnc found no evidence for coherent oscillations either in quiescence or during eruptions. But van Paradijs et al. (1994) found that orbital variability was present during quiescence.

In X-ray band, YZ Cnc has also been studied very extensively with the Einstein satellite (Córdova & Mason 1984, Eracleous et al. 1991), with EXOSAT (van der Woerd 1987), with the ROSAT PSPC during the ROSAT All Sky Survey and in subsequent pointings (Verbunt et al. 1997, 1999; van Teeseling & Verbunt 1994), and with XMM-Newton (Hakala et al. 2004).

However, spectroscopy has not been as extensive as photometry or X-ray, specially when the system is undergoing superoutburst. The sporadical spectroscopic observations have been performed by several authors as part of general surveys of cataclysmic variables (Szkody 1981, Oke & Wade 1982, Wade 1982, Williams 1983). Shafter & Hessman (1988, named SH hereafter) presented a detailed spectroscopic study of YZ Cnc when the star was in quiescence and gave an orbital period of 0.0868(2) day. According to this orbital period and the superhump period given by Patterson (1979), a precessing period of 1.52 day can be obtained. We thus did a 2-days observation to study the accretion disk of YZ Cnc during its 2002 January superoutburst. In this paper we report our observations and reduction of the spectroscopic data in Sect. 2. In Sect. 3 we describe the main characteristics of the spectroscopic results and explanations for these results. In the last two sections we present a brief discussion and conclusions for this work.

2 OBSERVATIONS

The observations were conducted with the Optomechanics Research, Inc., Cassegrain spectrograph attached to the 2.16-m telescope with a TEK1024 CCD camera at Xinglong Station of the National Astronomical Observatory. Total observational time was 11 hrs, 5.3 times of the orbital period. A 300 groove mm^{-1} grating blazed at 5000 Å was used, and the slit width was set to $2''.5$. Dome flats were taken at the beginning and end of each night. Exposure time for the star ranged from 600 to 1800, depending on weather

Table 1 Journal of observations.

Date (UT)	HJD Start	Duration	Exposure	Plates
(Year 2002)	-2452000	(hr)	(s)	
Jan 21	296.1457	5.22	900,1200	15
Jan 22	297.1064	5.78	1500	14

conditions. Fifteen and fourteen star spectra were collected on January 21 and 22 (Beijing time), respectively. The journal of the observations is listed in Table 1.

The technique of data processing is similar to that in Wu et al. (2001). After bias subtraction and flat field correction, we used the *IRAF*¹, task *cosmicray* to eliminate the cosmic rays roughly and then used *imedit* to get the cosmic rays rejected more clearly by hand. The lamp spectra recorded before and after every two successive star exposures were used to interpolate the coefficients of the wavelength scales. We derived a spectral resolution of 12 Å from FWHM measurement of the lamp spectra. The rms error of identified lines was less than 0.2 Å using a fourth-order Legendre polynomial to fit the lines, corresponding to 12 km s⁻¹ near H β . The flux was calibrated used the standard star, HD109995, and had an estimate error of $\sim 10\%$.

3 RESULTS AND ANALYSIS

3.1 Average Spectra

Fig. 1 shows the average spectra of YZ Cnc during its superoutburst. The top and lower panel are the sum of all 15 individual spectra recorded on January 21 and the sum of all 14 individual spectra obtained on January 22, respectively. The spectra of January 21 is characterized by broad Balmer absorption and an energy distribution significantly bluer than that of January 22, when the eruption was fading out. This spectra is typical of an optically thick accretion disk with a high accretion rate. The emission component came out and was specially stronger in H β absorption on January 22. The He I ($\lambda\lambda 4471, 4922$) absorption, He I $\lambda 5015$ +Fe II $\lambda 5018$ and Fe II $\lambda 5169$ absorption (emission on January 22) are also present (see more clearly in Fig. 2). The equivalent widths of the absorption and emission lines are summarized in Table 2.

3.2 Radial Velocity

In Fig. 2A we show the normalized spectrum which is the sum of all 15 individual spectra obtained on January 21. And Fig. 2B shows the normalized spectrum obtained on January 22. When combined, no radial velocity shift was applied.

¹ IRAF is distributed by the National Optical Astronomy Observatories, which is operated by Associated of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

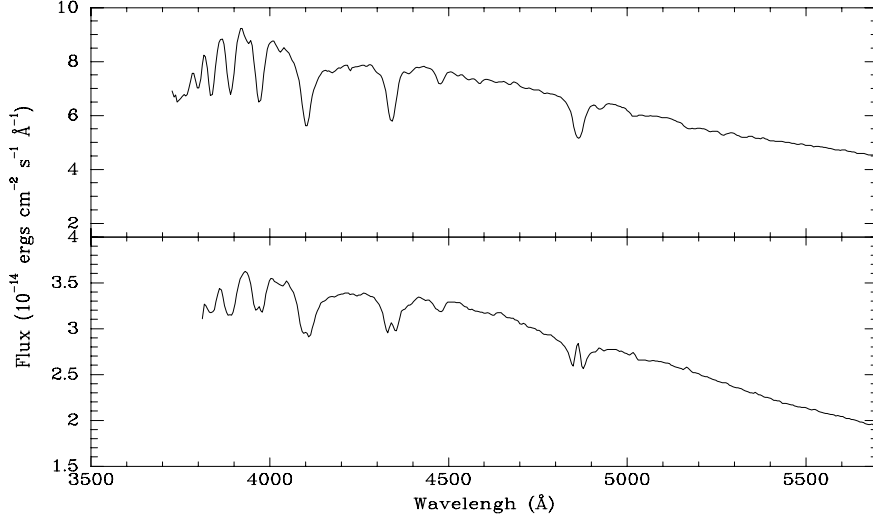


Fig. 1 Spectra of YZ Cnc during superoutburst. The top spectrum, obtained on January 21, is much bluer and the flux is also much higher than the bottom one, obtained on January 22.

Table 2 Equivalent widths of spectral lines.

Date (2003)	Element Rest Wavelength	EW (Å)	Element Rest Wavelength	EW (Å)
Jan 21	H ζ λ 3889	-6.2	H β λ 4861	-8.5
	H ϵ λ 3970	-6.9	He I λ 4471	-1.7
	H δ λ 4101	-11.3	He I λ 4922	-0.9
	H γ λ 4340	-8.2	He I λ 5015+Fe II λ 5018	-1.7
Jan 22	H ζ λ 3889	-4.2	H β λ 4861 (emission)	1.3
	H ϵ λ 3970	-4.7	H β λ 4861	-5.2
	H δ λ 4101	-8.9	He I λ 4471	-1.3
	H γ λ 4340	-7.6	Fe II λ 5169 (emission)	0.18

We measured the centers of H β absorption troughs of January 21 and emission peaks of January 22 with Gaussian-fit method. We used H β line because it had good signal-to-noise ratios in both nights. Fig. 3 shows the velocities folded on the orbital period with the best-fit sinusoidal curve superposed. The orbital phase was computed according to the ephemeris given by SH,

$$T_0 = HJD2,446,113.794 + 0.0868(2)E$$

where T_0 is the time of the γ crossover from negative to positive velocities and E is a cycle number. The best-fit sinusoidal shows that H β has an amplitude, K , of 49 ± 10

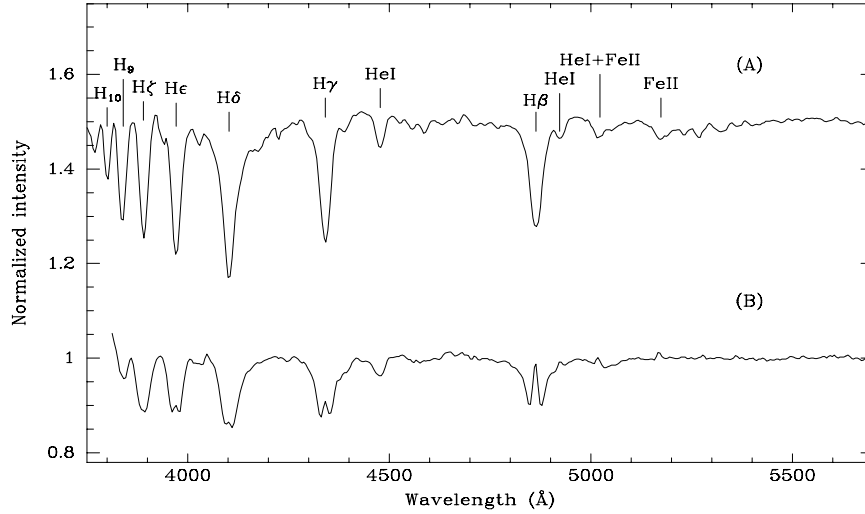


Fig. 2 Normalized average spectra of YZ Cnc during superoutburst.

(A):observed on January 21; there was no emission component in *all* spectral lines. (B): observed on January 22; almost all Balmer absorptions were partially filled by emission on this day. The emission component also came out in He I $\lambda 5015$ +Fe II $\lambda 5018$ absorption. Moreover, the Fe II $\lambda 5169$ had gone into emission. These differences showed that the star was going back to quiescence.

km s^{-1} and a systemic velocity, γ , of $62 \pm 7 \text{ km s}^{-1}$. The value of K is very consistent with the result of SH, $50 \pm 20 \text{ km s}^{-1}$, which was measured during the quiescence. But the γ velocity is somewhat larger than the value of $\sim 16 \text{ km s}^{-1}$ in SH.

It is clearly shown in Fig. 3 that there are two abnormal points near phase 0.6 and 1 whose velocities are much larger than the others'. This maybe occur at the accretion flow.

3.3 An Eccentric Disk

3.3.1 The variation of γ and orbital-averaged velocity

In Fig. 3, we show the radial velocities marked with filled and open triangles, corresponding to January 21 and 22, respectively. It can be seen clearly that there is a systemic discrepancy between these velocities obtained in these two days. We have used the sky emission line 5577\AA to check whether this occurred due to the systemic error and the difference between these two days is less than 0.2\AA . So we believe the existence of discrepancy between these two γ velocities is real. And we derived these two γ velocities from fitting sinusoidal to the data shown in Fig. 3 (excluding the two abnormal points

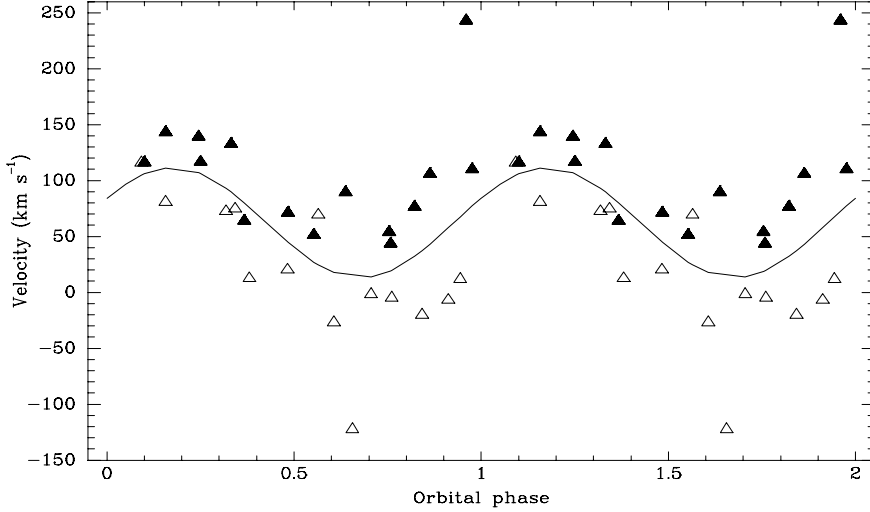


Fig. 3 Least-squares sinusoidal fitted for the radial velocities of the centers of $H\beta$ obtained on January 21 and 22, representing with filled and open triangles respectively. Note that almost all velocities in the first night are larger than those in the second night. And it clearly shows that there are two abnormal points near phase 0.6 and 1 whose velocities are much larger than the others'. This maybe occur at the accretion flow.

near the phase of 0.6 and 1.0, also see Fig. 4) as 91 km s^{-1} and 34 km s^{-1} , for January 21 and 22 respectively.

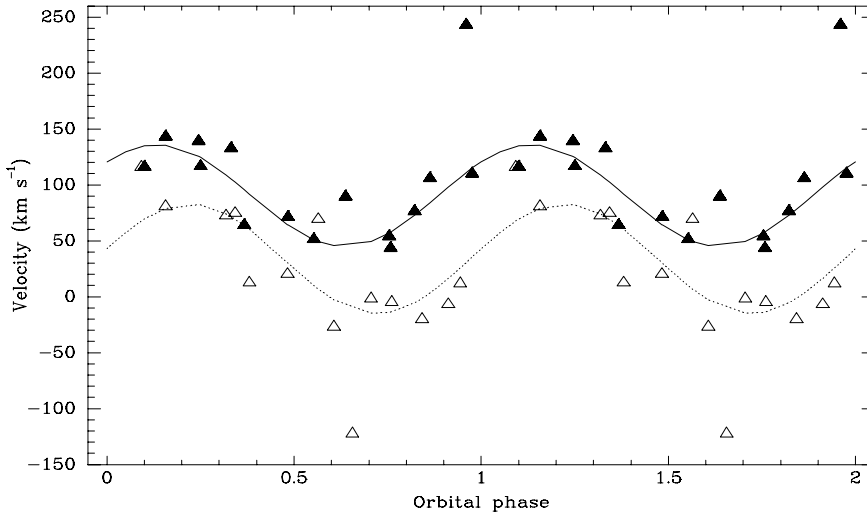
We also measured the centers of $H\beta$ of the average spectra of these two days. And we obtained that the relative velocities, which are averaged throughout the orbital period, are 97 km s^{-1} and 28 km s^{-1} , corresponding to January 21 and 22, respectively. This phenomenon was also found in IY UMa (Wu et al. 2001), KS UMa (Zhao et al. 2005a). These two features of our radial velocities are summarized in Table 3.

3.3.2 The large phase shift of ~ 0.09 between two days

As shown in Fig. 4, there obviously existed a phase shift of ~ 0.09 between the two sinusoidal velocity curves of January 21 and January 22, as shown by continuous and dashed line respectively. This feature of the radial velocities is discovered for the first time for YZ Cnc, even for SU UMa stars. Such big phase shift in one day could not be due to the uncertainty of the orbital period because the error of the orbital period of 2×10^{-4} day given by SH only gives a phase shift of ~ 0.026 , which is in agreement with the phase offset on January 22. So there must exist some other reasons responding for

Table 3 The γ velocity, K , phase offset and orbital-averaged velocity

Date (UT)	γ	K	Phase offset	$V_{average}$
(Year 2002)	(km s ⁻¹)	(km s ⁻¹)		(km s ⁻¹)
Jan 21	91±4	46±5	-0.12±0.02	97±12
Jan 22	34±6	49±9	-0.03±0.03	28±10
Shift	57±7	...	0.09±0.04	69±16
Jan 21 & 22	62±7	49±10	-0.07±04	...

**Fig. 4** Phase shifted in two days. The least-squares sinusoidal fitted results for the radial velocities on January 21 (filled triangles) and 22 (open triangles) are present with solid line and dashed line, respectively. It is obviously that there existed a shift (~ 0.09) between the phases in these two days.

this phenomenon. The feature of phase shift of our radial velocity curve is also listed in Table 3.

3.3.3 An eccentric disk

The phenomena described above can be well explained with a slow precession of an eccentric outer disk. The relative velocity (line-of-sight component) at point $r(\theta)$ on the boundary to white dwarf is (Wu et al. 2001)

$$V(r, \theta) = C[-e \sin(\theta_0) - \sin(\theta + \theta_0)] \quad (1)$$

where $C = \sin i \sqrt{\frac{GM_1}{a(1-e^2)}}$ = constant; i , a and e are the inclination, half of the major axis and eccentricity of the accretion disk, respectively. Hence, the mean velocities of the

troughs of the absorption lines or the peaks of the emission lines are $V = -Ce \sin(\theta_0)$. According to this equation, the increase of θ_0 will lead to the result that the central wavelengths of spectral lines, i.e., the orbital-averaged velocity, will be variable with the precessing phase of the disk.

Generally, the γ velocity is thought to represent the systemic motion of the binary. This is correct provided that the accretion disk was axis-symmetry. If the material in the ring surrounds the primary is not in circular orbits, i.e., the accretion disk is eccentric and processing, then white dwarf will be at one of the focus and the mass center of the system (nearly locating at the geometry center) would change with the precession period of the disk. Thus, the systemic velocity, i.e., the γ velocity, maybe also change with different precession phase of the disk.

The large phase shift of ~ 0.09 between these two days shows that the variation of the centers of the absorption or emission peaks can not represent the movement of the white dwarf. And this phenomenon can also been interpreted with a slow precession of an eccentric disk. As described above, the position of the mass center of the system will vary with the precession of the disk. This would lead to the variation of the time (T_0) of the γ crossover from negative to positive velocities, resulting in the phase shift with the disk at different precession phase.

3.3.4 A constraint on the eccentricity

The precessing period (P_{prec}) of the disk is the beat period of the orbital period (P_{orb}) and the superhump period (P_{sh}). It can be written as

$$\frac{1}{P_{prec}} = \frac{1}{P_{orb}} - \frac{1}{P_{sh}} \quad (2)$$

According to Eq. (2), the precessing period of YZ Cnc is 1.52 days, computed with $P_{orb}=0.0868$ day, given by SH and $P_{sh}=0.09204$, given by Patterson (1979). Thus, θ_0 will increase 4.12 rad within 1 day. So we have the mean velocities of the absorption troughs to be $-Ce \sin(\theta_0)$ on January 21, the emission peaks to be $-Ce \sin(\theta_0 + 4.12)$ on January 22. Comparing their difference with the measured data (the shift of “ $V_{average}$ ” in Table 3), we have

$$Ce \cos(\theta_0 + 2.06) = 60 \quad (3)$$

If we know the value of C , i.e., know M_1 , a , q and P_{orb} , we can give a constraint on the eccentricity of the disk.

3.4 Mass and Inclination

The mass and inclination of stars are very difficult to be determined if the system is not eclipsing. SH used the properties of the emission lines (specially the linewidth) to provide a relation between the inclination and the white dwarf mass with an empirical

assumption that the velocity from the line center at 30% of the emission-line intensity best represents $V_d \sin i$. They gave that the mass of the secondary is $\sim 0.17 M_\odot$ and $0.75\text{--}0.9 M_\odot$ of the primary.

Substituting P_{orb} with $0.0868(2)$ day in equation (1) in Zhao et al. (2005a), we have

$$M_1 = M_2/q, \quad M_2 = [0.829(1 + 1/q)^{1/3}Q(q)]^{15/7} \quad (4)$$

We can obtain the mass ratio by using an empirical relation found by Patterson (2001), $\epsilon = 0.216(\pm 0.018)q$, where $\epsilon = (P_{sh} - P_{orb})/P_{orb}$. It gives $q = 0.28 \pm 0.03$, which is somewhat larger than that of SH.

According to equation (4), it is only requires $q > 0.09$ to meet the condition that the white dwarf mass should be less than $1.44 M_\odot$. The mass ratio of 0.28 ± 0.03 derived above is consistent with this requirement. Therefore we can obtain that $M_2 = 0.13 \pm 0.01 M_\odot$ and $M_1 = 0.46 \pm 0.06 M_\odot$. Using the $K_1 = 49 \pm 10 \text{ km s}^{-1}$ (see §3.2), the mass function $f(M) = (M_2 \sin i)^3 / (M_1 + M_2)^2 = K_1^3 P_{orb} / (2\pi G) = 0.00106(10) M_\odot$ gives $i = 34^\circ \pm 9^\circ$.

The values of M_1 and M_2 are smaller than those of SH. This is believed due to the systemic difference between different methods and some unproved empirical assumptions. Hence, the masses and inclination given here are rather uncertain.

4 DISCUSSION

The variation of γ velocity discovered in YZ Cnc is for the first time but not alone. It has been discovered in several other SU UMa stars, i.e., Z Cha (Vogt 1982, Honey et al., 1988), KS UMa (Zhao et al. 2005a) and ER UMa (Zhao et al. 2005b). As described by these different groups, the RV curves for different CVs are *all* gotten by measuring spectra obtained when the stars went through *eruptions*.

Vogt (1982) and Honey et al. (1988) have found that the γ velocities of Z Cha varied during its superoutburst. Vogt (1981) proposed a model in which he considered the behavior of a precessing, elliptical ring surrounding a circular accretion disk. This gives the variation of the γ velocity on a night-to-night basis as a result of variations in the projected motion of the ring material against that of the inner (circular) disk. Honey et al. (1988) interpreted their observational result with new non-axisymmetric disk simulations as arising in an eccentric, precessing disk which is tidally distorted by the secondary.

Our results that the γ velocity vary with time and that the phase shifts between different days are based on the measurement of centers of the absorption troughs of $H\beta$ and the centers of the peaks of the emission cores. We can not help but do this. We can't use the double-Gaussian convolution method (Shafter et al. 1988) to measure RV because the wings of $H\beta$ are blended with He I $\lambda 4922$ and the other Balmer lines not only are contaminated but also have bad signal-to-noise ratio, especially on January 22. Despite of this, our observational result confirmed that the γ velocity do actually vary when the star was ongoing a superoutburst.

We find for the first time that the phase of the system would change. If we believe that the orbital period and the error given by SH are reliable, the phase shift between these 2 days does actually exist. It is not surprised that this phenomenon can be found in YZ Cnc between 2 days because the precession period of YZ Cnc is only 1.52 days. The phase shift is enough to be observed between 2 days. So our observation provides more evidences to convince us that the accretion disk is precessing and eccentric when the binary system going through superoutburst. If the system has a larger inclination, we could get more information and do more detailed analysis like IY UMa (Wu et al. 2001) and KS UMa (Zhao et al. 2005a).

We can also estimate the eccentricity crudely by substituting the mass of the white dwarf M_1 , the mass ratio q and the inclination i , with the values given above (see §3.4), we obtained

$$\cos(\theta_0 + 2.06) = 0.231/e$$

If we substituted these parameter with the values given by SH, we would get

$$\cos(\theta_0 + 2.06) = 0.184/e$$

So e must be larger than 0.184 or 0.231, according to whose parameters are more reliable.

5 CONCLUSIONS

So far, we have shown the properties of our spectra and the radial velocities of YZ Cnc obtained during its 2002 January superoutburst. These properties include following three aspects,

(1) The γ velocity ($62 \pm 7 \text{ km s}^{-1}$) obtained in these two days deviated strongly from the systemic velocity ($16 \pm 10 \text{ km s}^{-1}$) measured by SH when the binary system was in quiescence. And there is a discrepancy of $\sim 60 \text{ km s}^{-1}$ of the γ velocities between these two days.

(2) The mean velocities averaged throughout the orbital period of these two days have large offset of the order of $\pm 70 \text{ km s}^{-1}$.

(3) There is large phase offset of ~ 0.09 between these two days.

As detailedly described in §3.3, we can make a conclusion that these features are all ascribing to the precession of an eccentric accretion disk. Therefore, we can make use of these properties to confirm whether the accretion disk is eccentric or not.

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